APPLICATION

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FILTER SYSTEM

CLAIM OR PRIORITY

[0001] The present application claims priority to co-assigned U.S. Patent Application No. 10/377,087 filed on February 28, 2003, entitled "Circuit for adjusting headroom across an active filter element."

BACKGROUND

[0002] Electronic circuits may include passive circuit elements, such as resistors and capacitors, and more complex, actively-controlled circuit elements which may provide logic and control functions. An example of an actively-controlled circuit element is a metal oxide semiconductor field effect transistor (MOSFET), which may be controlled to perform a switching function, e.g., turned on and off, or controlled in a linear fashion, e.g., voltage across the MOSFET or current flowing in the MOSFET may be controlled over a continuous range of values.

[0003] Circuit elements may be formed as regions of materials on a substrate as part of an integrated circuit. Alternatively, circuit elements may be commercially available as discrete passive and active devices mounted on a circuit board using conventional soldered leads or surface mounted contact pads.

[0004] Some circuit components may serve secondary services or functions for primary circuit components. For example, a power converter circuit may be considered a primary circuit, while a ripple filter component coupled to the output of the power converter may provide a secondary service function. Primary circuit components may be sold as commercial products, and service functions may be

provided by components that are sold and mounted separately. Alternatively, one or more service functions may be included directly in a primary circuit component.

SUMMARY

[0005] The present disclosure relates to a filter system. One embodiment of the filter system comprises two or more filter circuits coupled in parallel between an input terminal, an output terminal and a reference terminal. The filter circuits may each supply a substantially equal current to a common external load.

[0006] An aspect of the disclosure relates to an apparatus comprising a first circuit. The first circuit comprises an input, an output, a reference terminal, a series pass device connected between the input and the output, and a control circuit. The control circuit is operable to (a) sense a series current flowing through the series pass device and (b) control the series pass device. The control circuit comprises a negative feedback loop to control an average power dissipation in the first circuit by comparing the series current with a signal at the reference terminal.

[0007] Another aspect relates to an apparatus comprising a first circuit. The first circuit comprises an input, an output, a reference terminal, a series pass device connected between the input and the output, and a control circuit. The control circuit comprises a negative feedback loop. The control circuit is operable to (a) sense a current flowing through the series pass device and (b) adjust the current flowing through the series pass device.

[0008] Another aspect relates to a method comprising sensing a first current produced by a first filter circuit;

and adjusting the first current to substantially match a second current produced by second filter circuit. The second filter circuit is in parallel with the first filter circuit.

[0009] Another aspect relates to an apparatus comprising a first controlled circuit element and a control circuit. The first controlled circuit element is adapted to output a first current. The control circuit is adapted to (a) sense the first output current from the first controlled circuit element; and (b) adjust current through the controlled circuit element when the first output current does not match a second output current of a second controlled circuit element.

[0010] The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, and advantages of the invention may be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Fig. 1A illustrates a circuit, which may be implemented on a circuit board or as an integrated circuit.

[0012] Fig. 1B illustrates a component which may be implemented in the circuit in Fig. 1A.

[0013] Figs. 1C-1D illustrate an input voltage versus time and an output voltage versus time, respectively, of the component in Fig. 1B.

[0014] Fig. 2 illustrates an embodiment of the component in Fig. 1B.

[0015] Fig. 3 illustrates a remote sense circuit.

[0016] Fig. 4A illustrates a filter circuit which may be implemented as the active filter circuit of Fig. 2.

[0017] Fig. 4B illustrates a load sharing circuit with a plurality of filter circuits which may be implemented in the active filter system of Fig. 2.

[0018] Figs. 5A-5D are voltage and current plots of the active filter circuit.

[0019] Fig. 5E shows a headroom resistance in parallel with a slope resistance versus the headroom resistance.

[0020] Like reference symbols in the various drawings may indicate like elements.

DETAILED DESCRIPTION

[0021] Fig. 1A illustrates a circuit 12, which may be implemented on a circuit board or as an integrated circuit. A secondary circuit component 14 may provide a secondary service or function for a primary circuit component 10 of the circuit 12. The secondary function may be provided by a selected number of secondary circuit components 14 in parallel. Each secondary circuit component 14 may include a controlled element 16, which may be controlled by a control circuit 18. The primary circuit component 10 may serve a wide variety of purposes, and the secondary circuit components 14 may provide a broad range of secondary functions or services to the primary circuit component 10.

[0022] Fig. 1B illustrates a system 202, which may be implemented in the circuit 12 of Fig. 1A. The system 202 may include an idealized active filter element 204 with an input terminal 206 and an output terminal 208. The input terminal 206 may be coupled to a non-ideal, input voltage source 207 (Vin). The output terminal 208 may be coupled to a unipolar output load 203. Capacitance may be coupled to the input terminal 206 of the filter element 204 to store charge. An output voltage Vout may be present across

an output load 203. A third terminal 210 of the filter element 204 may be grounded.

[0023] Fig. 1C illustrates an input voltage versus time, and Fig. 1D illustrates an output voltage versus time of the system 202 of Fig. 1B. The active filter element 204 may reduce or prevent ripple voltage 209 generated by the input voltage source 207 from appearing in Vout at the load 203 by controlling an active element, such as a transistor, to offset the ripple 209. "Active filtering" may refer to a filter circuit having an actively-controlled circuit element for implementing a filter function.

[0024] Fig. 2 illustrates an embodiment of the system 202 in Fig. 1B. The system 202 may include a power converter circuit 300 coupled to an input terminal 206 of an active filter circuit 405. An output terminal 208 of the active filter circuit 405 may be coupled to an external load impedance (Zload), such as a circuit of resistors, inductors, capacitors and/or other elements.

[0025] A conventional DC-to-DC power converter may include ripple filtering circuitry. Certain applications may require very low ripple, and additional filtering requirements may be met by adding a filter component to the output terminal of the power converter. The active filter circuit 405 in Fig. 2 may attenuate undesirable alternating current (AC) components (Fig. 1C) of the input voltage Vin from the power converter circuit 300 that is seen at the output Vout. The active filter circuit 405 does not appreciably affect the AC voltage component at Vin, rather the active filter circuit 405 reduces the resultant AC voltage component seen at Vout. The active filter circuit 405 delivers voltage Vout to the load impedance Zload. For example, in some implementations, the active filter circuit

405 may be able to reduce the amount of ripple present on input voltage Vin that is seen at the output Vout by approximately twenty to forty decibels.

[0026] The active filter circuit 405 in Fig. 2 may include one or more controlled elements, e.g., pass device 250, and control circuits 400 to provide filtering functions to a primary circuit 10 (Fig. 1A). The controlled element may be an active filter pass device 250, such as a metal oxide semiconductor field effect transistor (MOSFET) or other type of controlled, active filter element. A control gate of the active filter pass device 250 may be coupled to a first internal terminal 212.

[0027] The active filter circuit 405 may include a reference resistor (Rvref) connected to a second internal terminal 210, which may be used to establish a reference voltage (Vref). Vref may used to establish a set point for an output voltage (Vout) at the output terminal 208, as explained below.

[0028] The active filter control circuit 400 in the active filter circuit 405 may control the quiescent voltage across the active filter pass device 250. The quiescent voltage or operating point of the active filter circuit 405 may be referred to as a "headroom voltage" (Vheadroom), which may be defined as the average difference between input voltage Vin and output voltage Vout.

[0029] The active filter control circuit 400 may respond to a decrease in load current Iload (current transferred to the external load Zload) by increasing the headroom voltage Vheadroom, which maximizes transient load response. The active filter control circuit 400 may respond to an increase in load current Iload by decreasing the headroom voltage Vheadroom, which reduces or minimizes power

dissipation of the pass device 250. Power dissipation, Pd, may be defined as approximately the product of the load current, Iload, (which is carried by pass device 250) and the headroom voltage, Vheadroom, across the active filter circuit 405.

[0030] The active filter system 202 may include an input capacitor, Cin, capable of storing additional charge, such that charge is available for subsequent additional load demand.

[0031] Vin may be adjusted to maintain Vout at a desired level. The active filter control circuit 400 may include circuitry to control the output (Vin) of the power converter circuit 300. For example, the active filter control circuit 400 may include a trim control circuit (not shown) to monitor headroom voltage Vheadroom and send or provide a signal to a TRIM terminal (Fig. 2) of the power converter circuit 300 to adjust the output of the converter circuit 300 (i.e., input voltage Vin).

[0032] Alternatively, Fig. 3 shows a remote sense circuit 501 which is capable of adjusting the output of the power converter circuit 300. The remote sense circuit 501 may include a resistor Rremote and a capacitor Cremote. The resistor Rremote is connected between Vout at Zload and a Sense terminal of the power converter circuit 300. The capacitor Cremote is connected between the Sense terminal and the converter output terminal 206.

[0033] The active filter circuit 405 of Fig. 2 may be implemented as illustrated in Fig. 4A. The filter circuit 450 may be a quiet power output (QPO) filter, which adjusts to dissipate relatively constant power and eliminates ripple, which was introduced by the input voltage Vin, as seen at the output Vout. The filter circuit 450 may

include an input terminal 452 for receiving an input voltage, Vin, an output terminal 454 for delivering an output voltage, Vout, and a reference terminal 460 for setting and/or monitoring a reference voltage, Vref. The filter circuit 450 may include a first amplifier 456, a second amplifier 458, a series pass device M1, a sense resistor, Rsense, a slope resistor, Rslope, a feedback resistor, RFB, other resistors R1, R2, R3, R4, R5, R6, R7, R8, Rheadroom, R10 and R11, and capacitors, C1, C2, C3, C4, C5.

[0034] As an example, the series pass device M1 may be a transistor, such as an n-channel enhancement type MOSFET. The first and second amplifiers may be operational amplifiers (op amps).

[0035] As discussed above, filter power dissipation may be reduced by lowering the headroom voltage in response to increased load current. Resistor, Rslope, may be chosen to set the slope of the filter's change in headroom voltage as a function of changes in load current. For example, the headroom voltage may be decreased by 150 mV in response to an increase in load current of 10 Amps. Rslope may be calculated using the following:

$$\mathrm{Rslope} = [(-a)(R10)(\mathrm{Rheadroom}) + (R10)(\mathrm{Rheadroom})] / [(\Delta VHR/\Delta Vi)(\mathrm{Rheadroom}) + a(R10 + \mathrm{Rheadroom})]$$

where

$$a = (R7 + RFB)/(R7 + RFB + R5 + R6)$$

$$\Delta Vi = (\Delta I)(\mathrm{Rsense})(R3/R1)$$

$$\mathrm{Rslope} = 1.789\ \mathrm{kohms}$$

[0036] With Iload = 0, Vout = Vref + Vos (amplifier 458A's input offset voltage), and therefore Vheadroom is approximately equal to (Vout/Rheadroom) x R10. Resistor Rheadroom is used to set the headroom voltage at no load

and is therefore referred to as Rheadroom in the above equations. Referring to Fig. 5E, Rslope as a function of Rheadroom does not change much for very large changes in Rheadroom. For example, variation of Rheadroom from 30 kohms to 300 kohms yields a calculated Rslope of 1.79 to 1.82 kohms. Therefore, Rslope may be selected first, and then Rheadroom may be changed to adjust the output voltage without necessitating an adjustment or recalculation of Rslope. Rheadroom is used to set Vheadroom. Other circuitry, either internal to the filter circuit 450 which acts upon a converter's "TRIM" or an external "remote sense" (Fig. 3) actually maintains the desired Vout.

[0037] RFB may be about 60 ohms. Rsense may be about 2 milliohms. R1 may be about 25 kohms. R3 may be about 250 kohms. R5 may be about 1 kohm. R6 may be about 2 kohms. R7 may be about 1 kohm. R10 may be about 2.5 kohms. R2 may be about 25kohms. R4 may be about 250kohms. R8 may be about 100 ohms. R11 may be about 10 ohms. Other resistance values may be used in other embodiments.

[0038] Bias voltage Vcc to each differential amplifier 456, 458 in Fig. 4A may be supplied by a built-in boost circuit, e.g., an inductive, non-isolated boost regulator or a switched capacitor boost circuit, which receives input voltage Vin and generates a voltage Vcc greater than the input voltage Vin. The V- (Vee) terminal of each amplifier 456, 458 may be connected to the output terminal 454 with output voltage Vout. In the filter circuit 450, a circuit may monitor the voltage difference between VCC and Vin and trigger a boost regulator to maintain this difference to some internally or externally programmable level(e.g., near 7.5 V).

[0039] The current sense resistor Rsense is preferably on the output side of the filter circuit 450 so that the drain D of the transistor M1 may be connected directly to a pad of a package (preferably a system in a package) to facilitate heat removal.

[0040] It may be preferable to integrate the filter circuit 450 into a three terminal device. For maximum versatility, the slope resistor Rslope and Rheadroom may be external to the three terminal device.

[0041] The capacitor C1 and resistor R8 may act as compensation to reduce the gain of the second amplifier 458 at high frequencies for stability.

[0042] In many applications it may be desirable to couple the filter circuit 450 of Fig. 4A in parallel with other filter circuits to handle large load currents. For example, a load current of 100 Amps may be filtered by connecting ten filter circuits (each capable of handling up to a 10 Amp load) in parallel.

[0043] One problem with connecting filter circuits in parallel is that very small differences in component characteristics, such as the input offset voltage or current, or the gain of one or more of the amplifiers, may cause one filter circuit to carry a disproportionate share of the load current. In high current load sharing applications, i.e., where many filter circuits may be connected in parallel, disproportionate sharing in the load could result in failure or destruction of the filter .

[0044] In accordance with one embodiment of the present disclosure, any number of filter circuits may be coupled in parallel to equally share in carrying a load current without an external controller.

[0045] Fig. 4B illustrates a load sharing circuit with a plurality of identical filter circuits 450A, 450B coupled in parallel to an input terminal (power source) 452, an output terminal (load impedance Zload) 454 and a reference voltage terminal 460. Each filter circuit 450 may be a three-terminal device. Vin, Vout and Vref will be the same for both filter circuits 450A, 450B. The two filter circuits 450A, 450B incorporate internal negative feedback circuitry that causes each filter circuit 450 to share equally in the load current as explained below. Thus, a system may be designed with two or more filter circuits 450A, 450B supplying a total load current that is equal to two or more times the current handling capability of one filter circuit 450.

[0046] In each filter circuit 450, resistors R1 and R2 are much larger than resistor Rsense. Rsense therefore provides a measure of the load current being carried by the individual filter circuit 450 and supplied to its respective output terminal 454. A first amplifier 456 amplifies the sensed load current signal and provides an output signal to the second amplifier 458. The voltage sensed by the difference amplifier circuit (comprised of resistors R1-R4 and amplifier 456) is Vrsense = Iload x Rsense, which is amplified by a gain of R3/R1 and provided as a voltage between pin1 of amplifier 456 and Vout.

[0047] The output current from the first amplifier 456 may be fed to the inverting input of the second amplifier 458 via the path with resistors R5, R6 and capacitor C2 and to the non-inverting input (of the second amplifier 458) via the path with resistors Rslope, Rheadroom and capacitor C3. The RC filter comprised of resistors R5, R6 and capacitor C2 may be selected to match the RC time constant

of a second RC filter comprised of resistor Rslope, resistor Rheadroom and capacitor C3, such that rapid changes in load current appear as a nearly pure common mode signal at the inverting and non-inverting inputs of the second amplifier 458. These RC filters also prevent the filter circuit 450 from rapidly acting upon sensed instantaneous changes in load current. In the instance of a single filter circuit 450, amplifier 456 serves only to adjust the average headroom voltage across the filter circuit 450 (via porting current through Rslope to Vref and altering the demand for current through resistor R10. In addition, with Iload > 0 A, Vpin1 of the first amplifier 456 will be greater than Vout, and therefore current will flow through resistors R5, R6, R7 and Rfb. The resultant offset voltage created across the input terminals of the second amplifier 458 will be canceled by an adjustment of Vin through one of the previously described feedback mechanisms to the power source 300. If two filter circuits 450A, 450B were coupled in parallel, the current through Rfb and the resultant differential voltage change seen by the input pins of the second amplifier 458 would cause the second amplifier's output voltage of the filter circuit 450 that had the higher share of the load current to fall and thereby reduce the current through its associated M1 pass device. Changes in load current are accommodated by sensing the resultant changes in Vout and adjusting the power source 300 to alter Vin through the mechanisms described above.

[0048] The differential input signal to the second amplifier 458 is substantially a comparison of the output voltage Vout and the reference voltage Vref. This feedback path (RFB) is used to provide the filter function, and

therefore has a greater bandwidth than the load-sharing feedback path. Average increases (or decreases) in the load current Iload increases (or decreases) Irslope (as a result of pin1 of amplifier 456 changing) which increases (or decreases) current IR10, which causes an increase (or decrease) in Vref, thereby reducing (or increasing) Vheadroom. As Vheadroom changes, Vout would tend to change, but feedback to the power converter 300 accommodates this change by altering Vin. The decrease in headroom voltage at high loads reduces power dissipation while increasing the headroom at low loads augments the transient response to changes in load current.

[0049] The filter circuits 450A, 450B in Fig. 4B are connected in parallel and share the same input terminals 452, output terminals 454, and reference voltage terminals 460. The reference voltages Vrefs are therefore forced to track each other. The voltage at the inverting pins of the amplifiers 458A, 458B, however, are not forced to track. The current through resistor RFB and the resultant differential voltage change seen by the second amplifier 458 cause amplifier 458's output voltage to fall and thereby reduce the current through its associated M1 pass device. The current sense negative feedback path therefore causes the filter circuits 450A, 450B to automatically share equally in the load current. The current across resistor Rsense may be sensed and controlled to be substantially equal in both filter circuits 450A, 450B. Average power dissipation may be substantially similar in both filter circuits 450A, 450B.

[0050] The resistor Rheadroom may be external to each filter circuit 450. Resistor R10 may be internal or external. If R10 is internal to the filter circuit 450, an

additional Rheadroom may be added for each filter circuit 450 so that the ratio of Rheadroom to R10 does not change. The effective value of Rheadroom may decrease as filter circuits 450 are added in parallel because internal R10 is also paralleled.

[0051] Each filter circuit 450 may be configured to avoid responding to changes or fluctuations in external load current.

[0052] R5, R6 and Rslope may make headroom voltage increase, decrease or stay constant with increasing load current.

[0053] If the current through Rsense in the first filter circuit 450A rises above the current through Rsense in the second filter circuit 450B, then the first Vrsense will be greater than the second Vrsense. The first amplifier 456A of the first filter circuit 450A effectively multiplies the first Vrsense minus the second Vrsense by a voltage gain of R3/R1. This amplified voltage is seen at the output of the first amplifier 456A with respect to Vout. This causes an increase in current flow from the first amplifier 456A, which may be divided proportionately between R5 and Rslope. The net effect of the increased current through Rslope upon the distribution of load current in the two filter circuits 450A, 405B may be negated because this current is fed into Vref, which is common to both. The increased current in R5 and R6, however, raises the voltage seen by the inverting input pin of the second amplifier 458A of the first filter circuit 450A. This lowers the second amplifier's output voltage, increases M1's impedance and reduces current through the transistor M1 of the first filter circuit 450A.

[0054] R5 and C2 may serve as an RC filter to slow the effects of the current change and minimize noise seen at

the second amplifier's inverting input pin. Rslope may reduce the voltage across the transistor M1 (drain to source) as current increases to minimize power dissipation.

[0055] Other aspects of the filter circuit 450 in Fig. 4A are now described. The capacitor C3 may derive a near direct current (DC) reference voltage Vref from the input voltage Vin. The capacitor C4 may store additional charge for subsequent additional load demands. Stored charge may also be available from output capacitance of the converter circuit 300.

[0056] The second amplifier 458 may forces its input terminal voltages to be substantially equal by driving its output to a level to which the transistor M1 pulls output voltage Vout to reference voltage Vref. For example, if voltage Vref is set to +11.5 volts, then the second amplifier 458 drives the transistor M1 to produce an output voltage Vout of +11.5 volts. The second amplifier 458 includes a feedback compensation network comprising capacitor C1, resistor R8 and resistor RFB for providing loop stability in conjunction with the second amplifier 458.

[0057] Figs. 5A to 5D are plots illustrating operation of the adaptive active filter circuit 405 of Fig. 2. In particular, Figs. 5A-5D illustrate how the adaptive active filter circuit 405 decreases headroom voltage Vheadroom as current Iload increases through the pass device 250. As a result, the adaptive active filter circuit 405 may maximize transient load response and minimize power dissipation across the pass device 250.

[0058] Fig. 5A shows a plot of load current Iload along the y-axis and time t along the x-axis. Fig. 5B shows a plot, along the y-axis, of input voltage Vin having a

positive peak voltage Vpeak_pos and a negative peak voltage Vpeak_neg, reference voltage Vref, output voltage Vout, and Vheadroom being the difference between Vpeak_neg and Vout. Fig. 5B shows time t along the x-axis.

[0059] At time t = 0, Fig. 5A shows Iload equal to a relatively low value of current, for example, 5 amps. Also at t = 0, Fig. 5B shows Vin having a DC voltage component and AC components of Vpeak_pos and Vpeak_neg, Vheadroom being the difference between the average Vin and Vout, and Vout being approximately equal to Vref. The active filter circuit 405 is able to drive output voltage Vout to a value set by Vref as well as establish the voltage Vheadroom across pass device 250. The active filter circuit 405 may attenuate ripple voltage represented by Vpeak_pos and -Vpeak_neg by approximately forty decibels.

[0060] At t = 30 milliseconds (ms), Fig. 5A shows load current Iload as it increases to the value Ipulse (e.g., approximately 10amps) for approximately 10ms until t = 40 ms when Iload returns to its original value of 5 amps. At t = 30 ms, Fig. 5B shows that voltage Vin decreases as a result of current Ipulse for a duration of 10 ms. However, the active filter circuit 405 maintains output voltage Vout at the reference level Vref despite an increase in Iload and resultant reduction in voltage Vin.

[0061] By providing additional headroom voltage Vheadroom at current less than its maximum rated load current for the active filter circuit 405, the circuit 405 is able to provide additional stored charge across the input capacitance, Cin in Fig. 2. The stored charge is available to provide additional load current, especially during short time periods (e.g., in the range about 0.1 to 1000 microseconds) due to transient changes in the

effective load impedance Zload. This may allow the active filter circuit 405 to maintain a nearly constant voltage across Zload, even under conditions of changing Zload. For example, increasing voltage Vheadroom from 0.2 to 0.5 volts may allow circuit 400 to handle these transient conditions.

[0062] In addition, the circuit 405 may be able to reduce Vheadroom to accommodate a longer term (e.g., time greater than 1000 microseconds) increase in Iload to minimize power dissipation. At low levels of operation, such as Iload being 5 amps and Vheadroom being 0.4 volts, power dissipation would be 2 watts. However, when load current Iload increases to 10 amps, the circuit 400 may reduce Vheadroom from 0.4 volts to 0.2 volts so as to maintain the power dissipation Pd of about 2 watts, approximately the same value of power dissipation at low levels of operation. This may permit the optimization of the design of systems using active filters, permitting reduced power dissipation to maintain an acceptable maximal temperature of the active filter and surrounding components.

[0063] Figs. 5C and 5D shows plots similar to Figs. 5A and 5B, except that Figs. 5C and 5D show the response of the filter circuit 405 to a smooth and linear increasing load current Iload instead of the sudden increase in Iload shown in Fig. 5A. Referring to Fig. 5D, Vheadroom decreases in response to increases in Iload through pass device 250, thereby maximizing transient load response and minimizing power dissipation across the pass device.

[0064] The techniques described above are not limited to the above implementation. A parallel filter system may use other types of filters, series regulators or active filters in parallel to increase a filter circuit's capacity to

provide load current. Other implementations may include, for example, active input or active output filters for switching power supplies, active filters for the input or output of AC-DC converters, active filters for AC-AC transformers or active filters used with linear or other non switching power supplies or filters used at a distance from a power converter among others.

[0065] Other implementations are within the scope of the following claims.